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**DESIGN GUIDELINE AND ACCEPTANCE CRITERIA FOR THE SAG BEND
COMPRESSION OF STEEL CATENARY RISER****Wei Ye**Ocean Dynamics LLC
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1600 Smith Street, Houston, Texas 77002, U.S.A.**ABSTRACT**

Although steel catenary riser (SCR) is an efficient riser concept for the deepwater oil and gas production, SCR on a Semi-submersible is susceptible to compression at the sag bend region that may lead to over stress under extreme environmental conditions such as 100-year and 1000-year return hurricane in Gulf of Mexico (GOM). It is one of the challenges to SCR design.

The paper covers a wide range of SCRs, ranging from 6 inch to 20 inch outer diameter and including production and export SCRs, under the 100-year and 1000-year return hurricane conditions in GOM. Both linear and nonlinear analysis is performed. The non-dimensional compression and stress/strain coefficients are proposed, and they reveal excellent correlations between them and the compression force and bending stress/strain despite of the different riser size and weight. These coefficients can be used to determine the level of compression and bending stress/strain before the detailed and lengthy calculations, which are very useful as design guidelines. The acceptance criteria for GOM 100-year and 1000-year return hurricanes are discussed. It is recommended that for the nonlinear strain-based design the collapsed-based strain acceptance criteria are not conservative. More stringent nonlinear strain-based criteria are recommended, such as fracture mechanics analysis and accumulated strain analysis to ensure the integrity of the SCR during its life span.

1 INTRODUCTION

Production Semi-submersible with SCR is a viable wet-tree solution to the GOM deep water environment. In recent years, the deep-drafted Semi-submersible has gained solid foothold in GOM due to its optimized motion performance. The Independence Hub Semi-submersible is the first deep-drafted Semi-submersible installed in the approximate 8000 ft water depth of GOM.

Although SCR is an efficient riser concept for the deep water oil and gas production, SCR on a Semi-submersible is susceptible to compression at the sag bend region that may lead to over stress under extreme environments such as 100-year and 1000-year return hurricane. It is one of the challenges to the SCR design. However, the over stress in SCR pipe does not necessarily leads to structural failure. The currently available industry design codes and practices do not provide a clear guidance to the compression and over stress issue. In addition, the SCR compression is a highly nonlinear behavior and is very sensitive to factors such as vessel motions, environment, drag force and weight etc., and therefore requires careful attention from the analysis side.

The widely used industry practice is that for the 100-year return hurricane the linear stress should be limited within 80% of yield stress and for the 1000-year return hurricane the linear stress should be limited within 100% of yield or the nonlinear bending strain should be less than the allowable collapse strain. However, the strain criteria based on collapse does not consider the accumulated plastic strain and the fracture development under the high strain condition therefore is considered to be not conservative. Kopp [1] recommended that the stain should be limited at 0.5% based on API RP 1111, DNV OS F101 and Appendix to API 1104.

McCan [5] studied the compression phenomenon and the numerical modeling technique for flexible risers in deepwater applications. Although its subject is the flexible riser, the conclusions are applicable to the SCR because the characteristics of the global responses for the flexible riser and SCR are very similar. McCan [5] examined in detail the buckling and post-buckling behaviors of deepwater risers, especially under the dynamic condition. He proposed a terminal velocity as an indication of the severity of the compression:

$$V_{Terminal} = \sqrt{\frac{2W}{C_d \rho D_{drag}}} \quad (1)$$

Where: W = submerged weight per unit length, C_d = drag coefficient, D_{drag} = drag diameter, ρ = water density.

Physically the terminal velocity is the riser downward velocity from which the Morison drag force is equal to the submerged weight of the pipe. When the riser downward velocity exceeds the terminal velocity, the riser will go into compression [5].

2 CASE STUDY

In order to demonstrate the SCR compression phenomenon, a case study has been performed for a production Semi-submersible and a wide variety of SCRs in the 7000 ft water depth in GOM. The 100-year and 1000-year hurricane conditions are shown as below:

- 100-yr Hurricane: JONSWAP, $H_s=15.0\text{m}$, $T_p=14.7\text{s}$, $\gamma=2.6$
- 1000-yr Hurricane: JONSWAP, $H_s=17.2\text{m}$, $T_p=15.2\text{s}$, $\gamma=2.6$

A uniform background current of 0.328 ft/s is assumed for both hurricanes.

The mean and slow-drifting offsets under the 100-year and 1000-year hurricane are assumed to be 6% and 8% of water depth, respectively. First-order motion RAOs from a generic Deep-drafted Semi are adopted to analyze the SCR response. The wave-frequency heave motion is the major driver to the SCR compression on a Semi-submersible.

The extreme strength analyses have been performed for the following SCRs:

- Production SCR #1 (OD 10.75 in x WT 1.38 in)
- Production SCR #2 (OD 10.75 in x WT 0.78 in)
- Oil Export SCR (OD 20 in x WT 1.25 in)
- Gas Export SCR #1 (OD 6.625 in x WT 0.5 in)
- Gas Export SCR #2 (OD 18 in x WT 0.92 in)

The material is API X65. Production SCR has 2.5 inch thermal insulation. All SCRs are fully straked.

Those SCR sizes are selected to represent a wide range of applications, i.e., high pressure vs low pressure production, oil field vs gas field etc, In such a way the findings in this paper are generally applicable to all SCRs and not limited to any particular size.

3 METHODOLOGY

Finite element (FE) models of the SCRs were created using riser analytical software Flexcom. The FE models are 11000 ft long for all SCRs. All FE models have approximately 2500 ft

resting on the seabed at vessel nominal position. Departure angles are 12 degrees for all SCRs. Strakes are used to cover all suspended length for all SCRs. The termination end of the SCR was fixed in all six degrees of freedom. At the top of the SCR, a flexible joint was modeled with the appropriate rotational spring stiffness. A seabed friction model was applied in the analysis in both the longitudinal and transverse directions.

The SCR FE models are discretized into 685 elements for all SCRs. Variable element lengths are used to maximize computational efficiency while maintaining solution accuracy. For each riser, element lengths of 3 feet and 0.5 foot were used in the critical flexible joint and sag bend regions, respectively. The length ratios of adjacent elements were kept below 1.5 to make transition smooth.

Riser static and dynamic analyses were performed using the Flexcom. For each load case, the vessel is moved to the offset location statically. Then, the corresponding environmental loads (currents & waves) were imposed in the same direction as the offset. Wave spectrum (JONSWAP) and piecewise current profile were applied. Three-hour time domain simulations were performed for all the cases studied. A fixed time step size of 0.1 second or less was used in all case runs. For the cases of 100-year and 1000-year hurricanes, five (5) 3-hour time domain simulations were performed for the linear analysis, and 3 3-hour time domain simulations were performed for the nonlinear analysis.

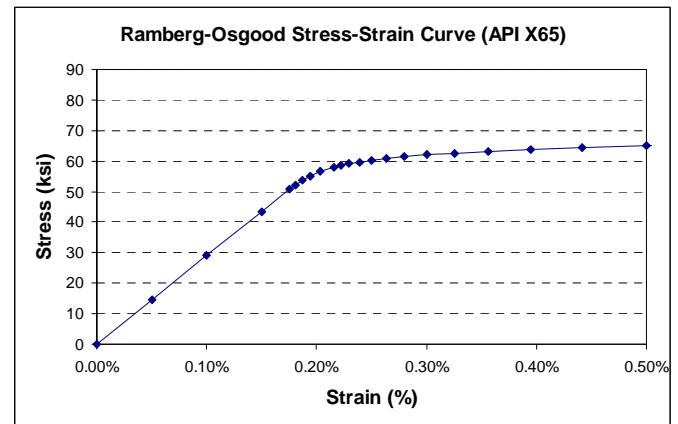


Figure 1 Ramberg-Osgood Stress Strain Relationship

For the nonlinear analysis, strain based analysis is adopted. Nonlinear elastic stress-strain (Ramberg-Osgood, Figure 1) relationship is used to model the nonlinear property. Since Flexcom requires the input in the format of bending moment versus curvature curve, the nonlinear stress-strain curve is converted to the moment-curvature curve by the integration of the bending stress across the cross-sectional area of the pipe. More specifically, the bending moment is given as $M(\rho) = \int \sigma(\rho, y) \cdot y \cdot dA$, where M is the moment, σ is the bending stress, ρ is the curvature, y is the distance of

stress point to the pipe cross section neutral axis, and A is the pipe cross section area. The moment curvature relationship of P1, SCR is presented in Figure 2. It should be noted that this curve does not account for the mean stress from tension and end cap pressure.

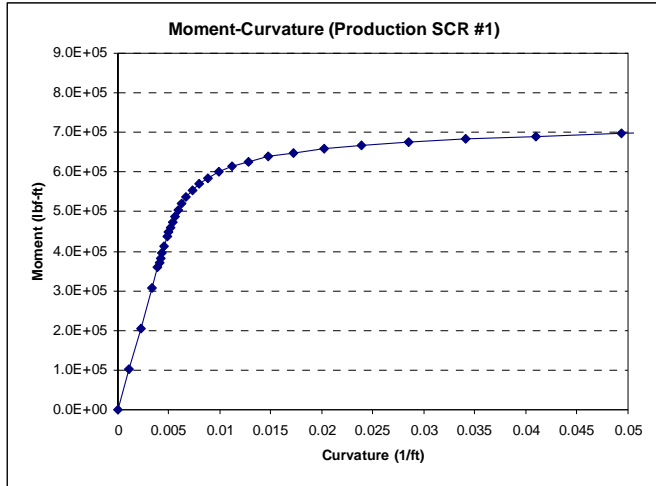


Figure 2 P1 Moment Curvature Relationship

4 ANALYTICAL RESULTS

The allowable strains based on API 2RD and API 1111 collapse criteria are presented in Table 1. For most of the cases except the 6-inch Gas Export SCR the API 1111 is more conservative than API 2RD. Compared with the recommended 0.5% strain [1], the collapse-based criteria seems not conservative. In addition, it should be noted that they are based on 0 psi pressure at the deck. Theoretically, if the pressure at the deck is considered and the internal pressure at the top down exceeds the external pressure, the local collapse will not happen. That is another reason why the collapse-based strain criteria are considered not conservative.

Table 1 Allowable Bending Strain

	Allowable Bending Strain	
	API RP 2RD	API RP 1111
P1	3.57%	2.83%
P2	1.72%	1.54%
Oil Export	1.79%	1.33%
Gas Export 6-inch	1.46%	1.28%
Gas Export 18-inch	0.56%	0.64%

The P1 100-year and 1000-year liner VM stress and nonlinear bending strain time histories are presented Figure 3 and Figure 4 respectively. The liner and nonlinear results are summarized in Figure 5 and Figure 6, respectively. For the linear analysis, there are 5 random simulations each for the 100-year and 1000-year hurricane condition. For the nonlinear analysis, there are 3

random simulations each for the 100-year and 1000-year hurricane condition. The allowable stress for 100-year and 1000-year hurricane based on API 2RD is 52 ksi (80% yield stress) and 65 ksi (100% yield stress). From the results, it is shown that for the linear results they are almost all over stressed for both 100-year and 1000-year cases and for the nonlinear results P2 and 6-inch Gas Export exceed the 0.5% allowable strain for the 100-year condition and the rest are within the limit. It is also demonstrated that for different SCRs the results are very scattered.

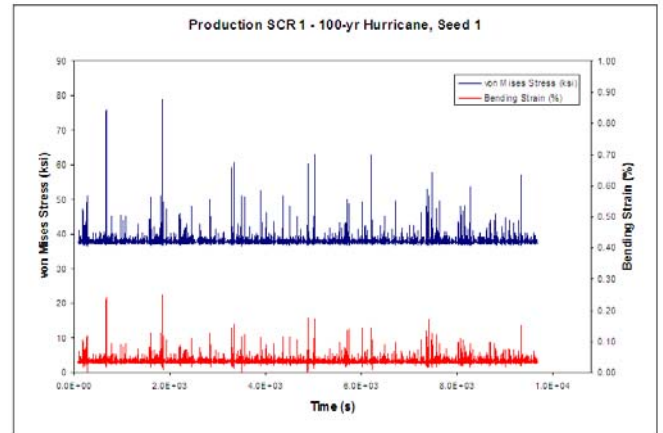


Figure 3 P1 Linear VM Stress vs. Nonlinear Bending Strain, 100-yr Hurricane

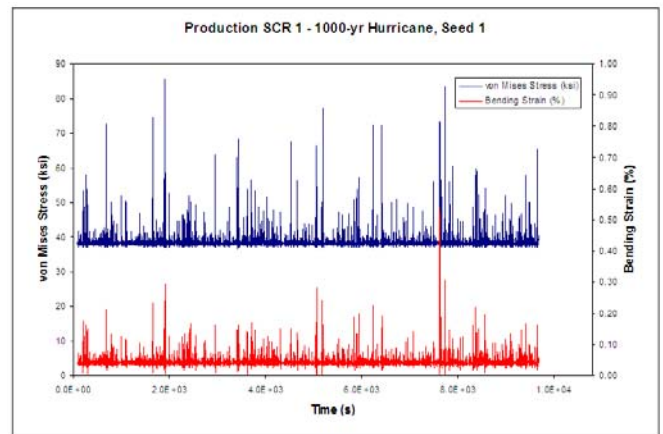


Figure 4 P1 Linear VM Stress vs. Nonlinear Bending Strain, 1000-yr Hurricane

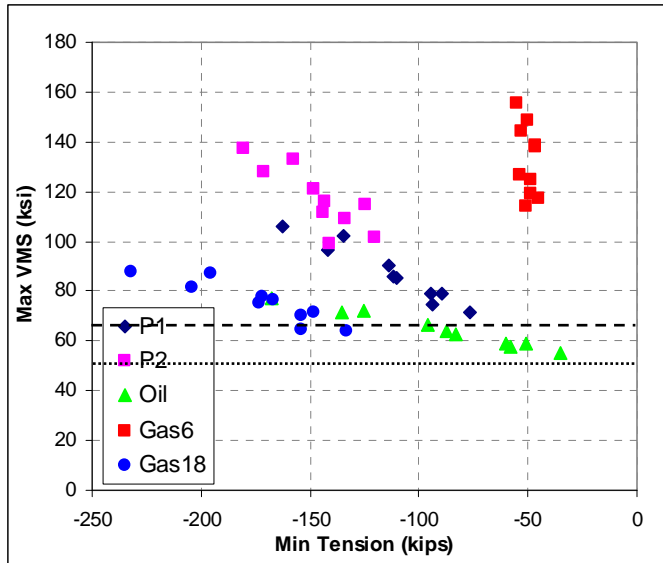


Figure 5 Linear Results

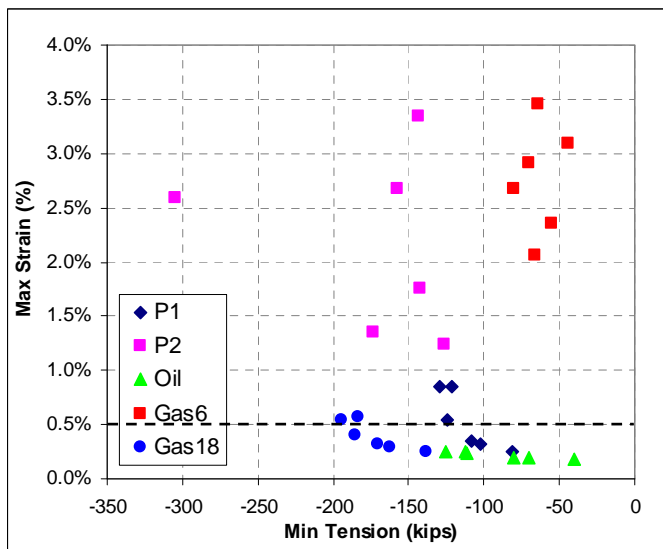


Figure 6 Nonlinear Results

In order to establish the trend of different SCRs, the relationship of linear maximum compression force and VM stress v.s. the non-dimensional velocity are shown in Figure 7 and Figure 8, respectively. The relationship of nonlinear maximum compression force and bending strain v.s. the non-dimensional velocity are shown in Figure 9 and Figure 10, respectively. The non-dimensional velocity \bar{V} is the ratio between the maximum velocity at SCR hang-off and the terminal velocity (Equation 2). For the compression forces, all but the 6-inch Gas Export SCR follow the same trend. For the VM stress or strain, they seem to follow nice trend but the 18-inch Gas Export SCR buckle the overall trend: it has a higher

non-dimensional velocity therefore should have higher compression, stress or strain but on the contrary it has higher compression but lower stress or strain. The reason is that it has a higher section modulus that lead to lower stress or strain.

$$\bar{V} = \frac{V_{\max}}{V_{\text{Terminal}}} \quad (2)$$

This prompts us to modify the non-dimensional parameter to include the effect of section area and modulus of the pipe:

$$\bar{B} = \frac{V_{\max}}{V_{\text{Terminal}}} \frac{\sqrt{gAT}}{WD^{3/2}} \quad (3)$$

$$\bar{C} = \frac{V_{\max}}{V_{\text{Terminal}}} \frac{WD^2}{\sqrt{gST}} \quad (4)$$

Where \bar{B} and \bar{C} are the non-dimensional compression coefficient and non-dimensional stress/strain coefficient; g is the gravitational acceleration; A is the cross section area of the pipe; T is the wave peak period; WD is the water depth; S is the section modulus of the pipe.

The relationship of linear maximum compression force v.s. the non-dimensional compression coefficient and linear maximum VM stress v.s. the non-dimensional stress coefficient are shown in Figure 11 and Figure 12, respectively. The relationship of nonlinear maximum compression force v.s. the non-dimensional compression coefficient and nonlinear maximum bending strain v.s. the non-dimensional strain coefficient are shown in Figure 13 and Figure 14, respectively. It is shown that with the modified non-dimensional parameters the results follow a better trend: for the linear compression (Figure 11), the 6-inch Gas Export SCR results fall into the same trend as the rest and they seem all to follow a linear regression; for the linear stress (Figure 12), the 18-inch Gas Export SCR results fall into the same trend as the rest and they seem all to follow a second-order parabolic regression, especially the average of each SCR results. Similar conclusion can be seen for the nonlinear results (Figure 13 and Figure 14). It should be noted that for P2 there is one random simulation for the nonlinear analysis seems to totally fall out of the league. Close examination reveals that the large compression and strain occur at the riser termination point rather than the sag bend region and it is most likely caused by the numerical error. Further improvement on the FE model by refining the mesh or increase the total riser length on the seabed should be able to eliminate this irregularity.

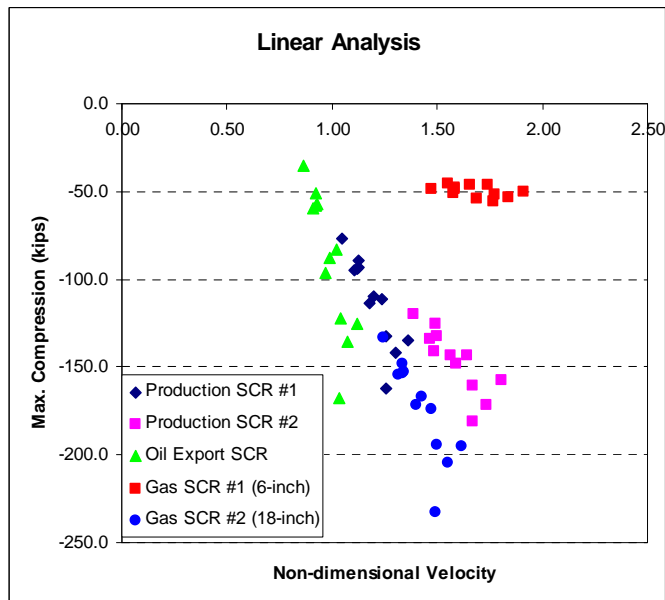


Figure 7 Linear Max. Compression vs. Non-dimensional Velocity

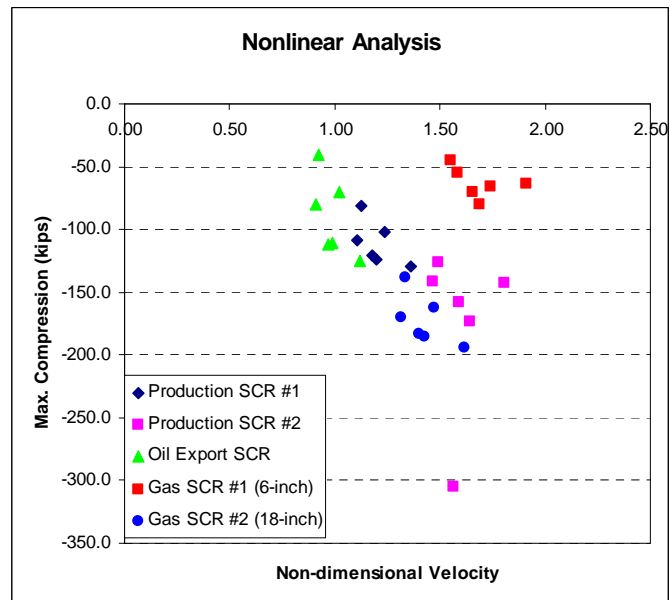


Figure 9 Nonlinear Max. Compression vs. Non-dimensional Velocity

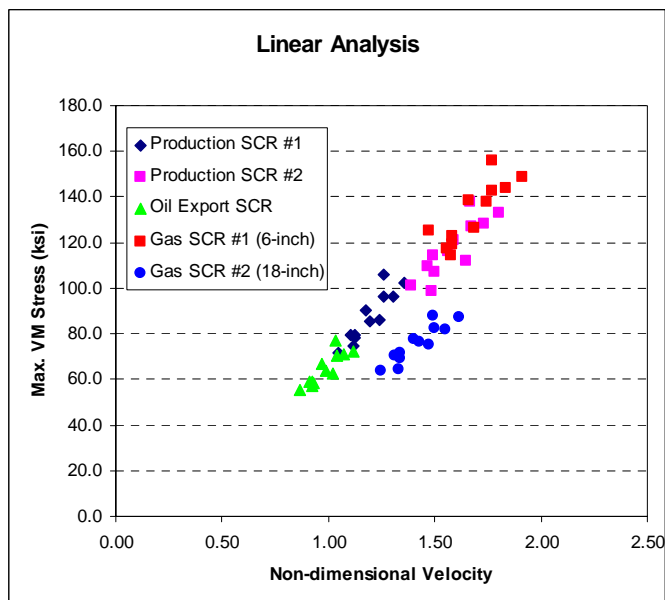


Figure 8 Linear Max. VM Stress vs. Non-dimensional Velocity

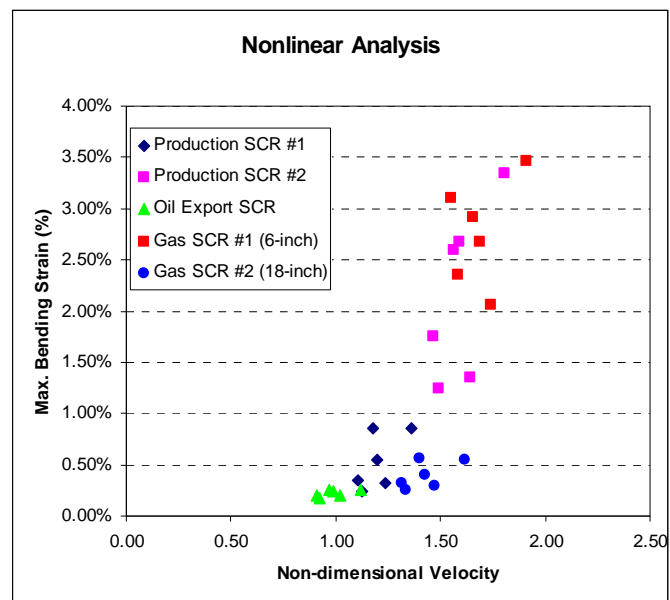


Figure 10 Nonlinear Max. Bending Strain vs. Non-dimensional Velocity

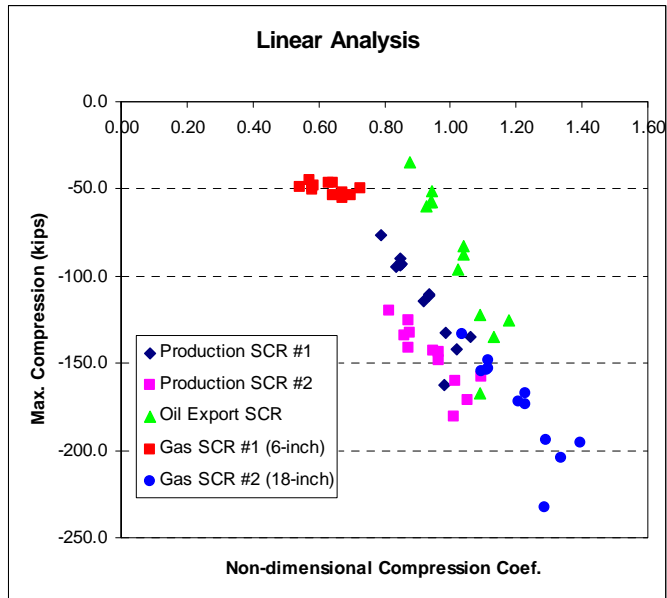


Figure 11 Linear Max. Compression vs. Non-dimensional Compression Coefficient

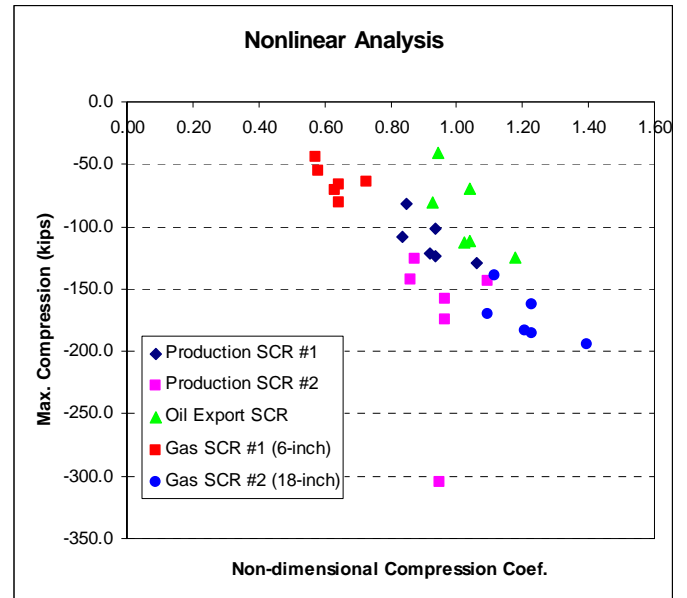


Figure 13 Nonlinear Max. Compression vs. Non-dimensional Compression Coefficient

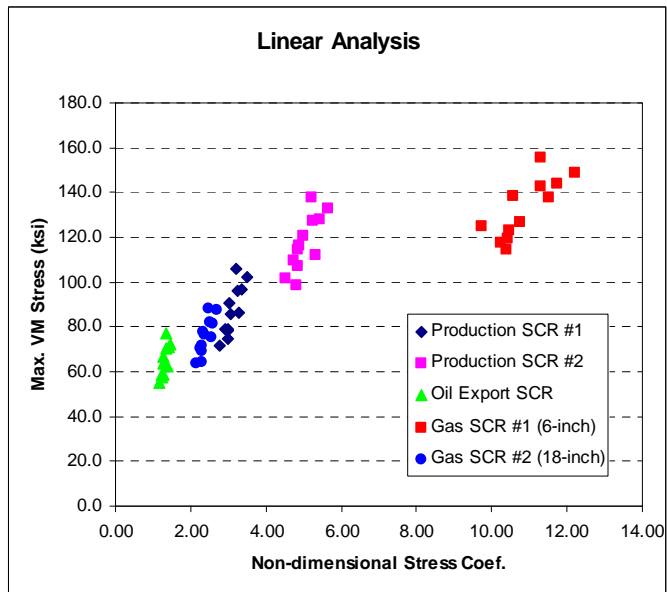


Figure 12 Linear Max. Bending Stress vs. Non-dimensional Stress Coefficient

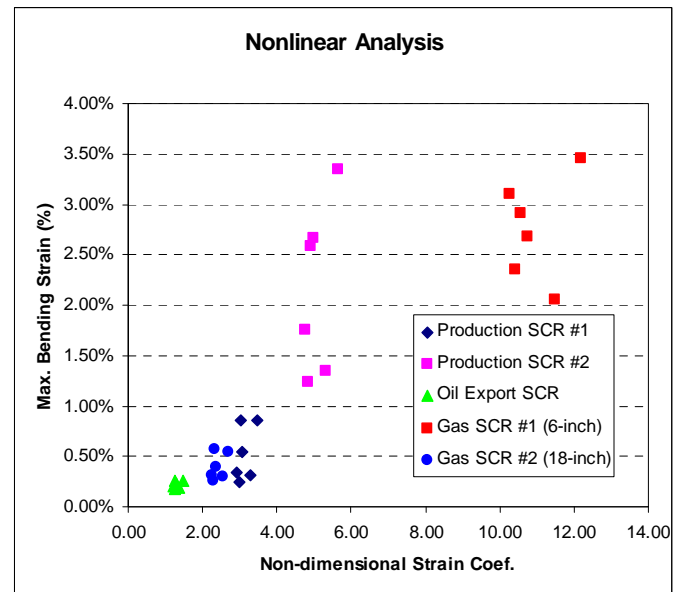


Figure 14 Nonlinear Max. Bending Strain vs. Non-dimensional Strain Coefficient

For the nonlinear strain-based analysis there is an alternative way to calculate the equivalent bending strain from the linear analysis on the basis of the equal energy. However, it is worth pointing out that this method tends to give unconservative results. The comparison of the equivalent bending strain from the linear analysis and the bending strain from the nonlinear analysis is presented in Table 2. It is shown that once past the yield point (0.2% strain) the equivalent strain method significantly under predicts the strain. The fundamental reason for the under prediction is because for the linear analysis the stiffness of the steel (E) is assumed to be constant while in reality it tends to decrease as the deformation (strain) becomes larger.

Table 2 Equivalent Bending Strain

		Equivalent Bending Strain Based on Linear Analysis	Bending Strain from Nonlinear Analysis
P1	100-yr	0.26%	0.25%
	1000-yr	0.29%	0.54%
P2	100-yr	0.42%	1.24%
	1000-yr	0.46%	2.67%
Oil	100-yr	0.19%	0.18%
	1000-yr	0.21%	0.24%
Gas 6"	100-yr	0.54%	2.35%
	1000-yr	0.59%	2.68%
Gas 18"	100-yr	0.25%	0.25%
	1000-yr	0.27%	0.40%

5 ACCEPTANCE CRITERIA

From the analysis results in Section 4, it can be seen that it is difficult to meet the linear stress criteria under both the 100-year and 1000-year hurricane condition. One of the reasons is due to the increase of environmental conditions after the recent intensified hurricane seasons. Another reason is the shut-in pressure included in the analysis. The VM stress is the equivalent stress that combines the axial, bending and hoop stress components, and the hoop stress that is caused by the differential pressure of the internal and external pressures contributes significantly to the overall VM stress. It is also shown that the collapse-based strain criteria are not conservative, certain more stringent restriction should be imposed to ensure the integrity of the riser system.

As to the acceptance criteria, it is recommended that for the 100-year hurricane condition the linear stress criteria is adopted and for the 1000-year hurricane the nonlinear strain criteria should be adopted. Alternatively, the strain criteria can also be considered for the 100-year hurricane condition. The following criteria are proposed for the GOM hurricane conditions:

- For the 100-year hurricane under both the intact conditions with dead oil/gas, the linear VM stress should be less than

80% of the yield stress. Under both the intact and damaged conditions (damaged mooring or tank) with shut-in pressure, the linear VM stress should be less than 100% of the yield.

- Alternatively, as the strain based criteria for the 100-year hurricane, the strain should be kept below 0.5%.
- For the 1000-year hurricane, the nonlinear bending strain should be within 0.75%, which is 50% increase from the 100-year condition. This is deemed reasonable because the 1000-year hurricane is only considered as robustness check by API RP 2RD. The strain should be also kept below the allowable collapse strain, although it is usually non-governing.
- In addition, if the strain based criteria is adopted, for both the 100-year and 1000-year hurricane condition, the fracture mechanics check or Engineering Critical Assessment (ECA) should be performed to ensure tearing and tearing fatigue are within the limit. In order to perform ECA check, nonlinear bending strain histogram are processed from the strain time histories based on rain-flow counting technique, as shown in Figure 15 and Figure 16.
- Furthermore, if the strain based criteria is adopted, the accumulated plastic bending strain should be checked and kept below 0.5% for the 100-year and checked against API RP 2RD and API RP 1111 for the 1000-year hurricane respectively. The hardening process and accumulated plastic strain is illustrated in Figure 17 and the results for the 5 SCRs are presented in Table 3.

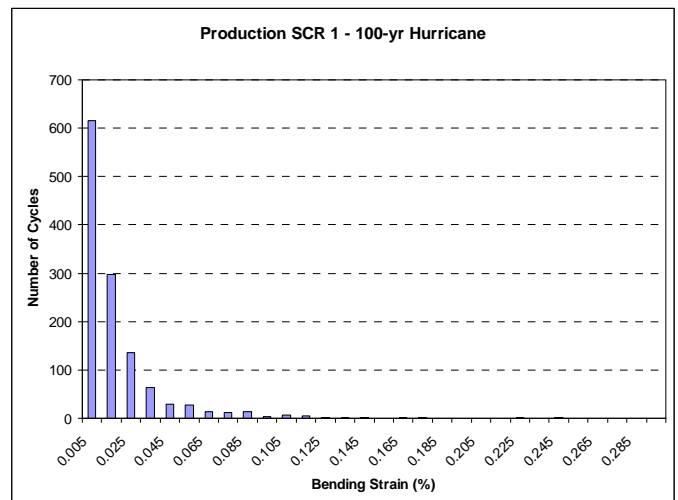


Figure 15 P1 – Nonlinear Bending Strain Histogram, 100-yr Hurricane

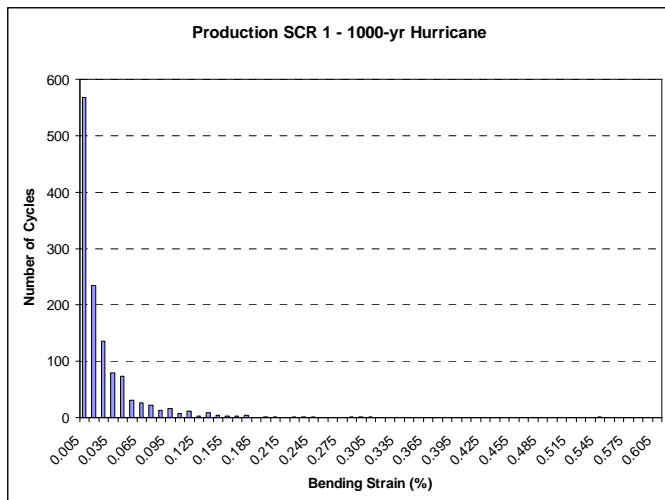


Figure 16 P1 – Nonlinear Bending Strain Histogram, 1000-yr Hurricane

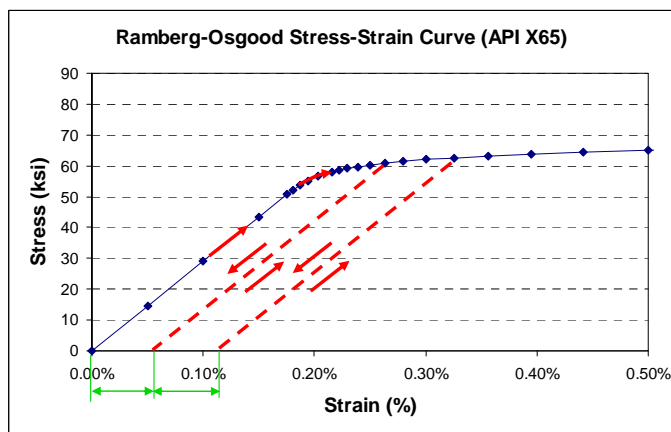


Figure 17 Steel Hardening Process and Accumulated Strain

Table 3 Accumulated Bending Strain

	Accumulated Bending Strain	
	100-year	1000-year
P1	0.12%	1.44%
P2	2.60%	4.62%
Oil Export	0.00%	0.08%
Gas Export 6-inch	14.18%	23.10%
Gas Export 18-inch	0.21%	1.44%

6 CONCLUSION

The paper covers a wide range of SCRs, ranging from 6 inch to 20 inch outer diameter and including production and export SCRs, under the 100-year and 1000-year return hurricane conditions in GOM. Both linear and nonlinear analysis has been performed. The non-dimensional compression and stress/strain coefficients are proposed, and they reveal excellent

correlations between them and the compression force and bending stress/strain in spite of the riser size and weight. These coefficients can be used to determine the level of compression and bending before the detailed and lengthy calculations, which are very useful as design guidelines.

The acceptance criteria for GOM 100-year and 1000-year return hurricanes are discussed. It is recommended that for the nonlinear strain-based design the collapsed-based strain acceptance criteria are not conservative. More stringent nonlinear strain-based criteria are recommended, such as fracture mechanics analysis and accumulated plastic strain analysis to ensure that crack does not develop during the life span of the SCR. It is also recommended that if this approach is adopted for design then more rigorous material testing and understanding of the steel hardening characteristics is required.

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